Optics Communications 297 (2013) 204–209

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Generation of three-atom Greenberger–Horne–Zeilinger entangled states based on separate cavities

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A R T I C L E I N F O

Article history:
Received 12 September 2012
Received in revised form
29 January 2013
Accepted 3 February 2013
Available online 27 February 2013

Keywords:
Entangled state
Cavity QED
Beam splitter

A B S T R A C T

An efficient scheme is proposed for the generation of a three-atom Greenberger–Horne–Zeilinger (GHZ) entangled state via three separate cavities. The scheme involves interaction-detection cycles and uses resonantly coupled atoms with an additional ground state not coupled to the cavity field. The important feature of our protocol is that the generation of the three-atom GHZ state can be realized with a certain probability according to the results of photon detectors and does not require performing any Bell-state measurements.

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1. Introduction

Quantum entanglement, one of the most striking features of quantum mechanics [1,2], yields a number of remarkable applications in quantum information-processing (QIP), such as, quantum cryptography [3], quantum dense coding [4], and quantum teleportation [5]. In all these QIP, entanglement plays the role of an indispensable and crucial resource that will be “consumed” during the QIP. It is well know that there exist various kinds of multipartite entanglement in reality, which have been investigated in many promising physical systems [6–9]. For instance, it is a fact that nonlinear systems containing separate Kerr-like oscillators, can behave as two- or three-level systems. The models based on such oscillators (nonlinear quantum scissors-NQS) can implement the generation of maximally entangled states. By far, entanglement generation via NQS has been reported by Refs. [10,11]. Besides, many proposals have been investigated based on cavity quantum electrodynamics (CQED) [12–14], and entanglements for distant atoms trapped in separate cavities are generated [15,16] by using the model proposed by Pellizzari [17] and Browne et al. [18], in which two distant particles are trapped in two optical-fiber-connected cavities.

With respect to three-particle states, it has been shown that there are two special and inequivalent classes of tripartite entanglement states, i.e., Greenberger–Horne–Zeilinger (GHZ) state [19] and W state [20]. In contrast with two-particle entangled state, GHZ states enable one to have an opportunity to measure quantum nonlocality without using Bell inequalities [19] and indeed have many important applications in quantum cryptography and quantum secrete sharing [21]. GHZ states are usually called as “a class of maximally entangled states” because of its maximal violation of Bell inequalities [22]. Due to their importance in QIP, GZH states have been received a great deal of attention, particularly the topic of its generation. To date, numerous schemes have been proposed for generating multi-particle GHZ state [23–26] in the frame of CQED.

Inspired by the coherent dynamic in Refs. [27,28], we will put forward to an effective scheme for the generation of a three-atom GHZ state based on several separate cavities. In the protocol, interaction-detection cycles are introduced by using resonantly coupled atoms with an additional ground state not coupled to the cavity field, and resonant atom–cavity interactions are required as well. Thus the interaction time is greatly shortened, which is important for suppressing decoherence and enhancing the success probability. In this proposal, each atom is trapped in its own cavity, and it is assumed that the photon leakage takes place from the side of the cavity facing the beam splitter. Then the leaked photons are detected by two photon detectors. Moreover, our current paper is to deal with the interaction of separate three-level atoms. In this scheme, the generation of three-atom GHZ state can be achieved with the help of a simple experimental setup. Since the current scheme is mainly based on the detection of the photon, if the photon emission is not detected, it fails and one can restart the procedure. For the sake of clarity, the process schematic has been shown as Fig. 1.

2. The generation of two-atom maximally entangled state

We consider that the atoms have two ground states $|g\rangle$ and $|f\rangle$, and one excited state $|e\rangle$, as shown in Fig. 2.

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http://dx.doi.org/10.1016/j.optcom.2013.02.008

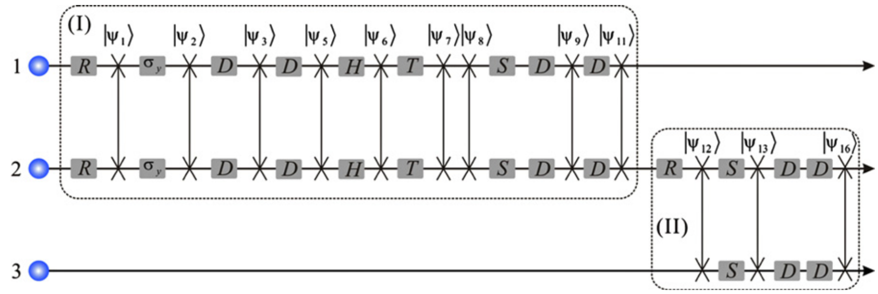

Fig. 1. Diagrams (I) the generation process of a maximally two-atom state, and (II) the generation process of a three-atom GHZ state. R represents a half-cycle of the vacuum Rabi oscillation of cavity field; σ_y represents a transformation $|f_i\rangle \to |g_i\rangle, |g_i\rangle \to -|f_i\rangle$; D represents the leaking photon is detected by the photon detector; H represents a transformation $|g_i\rangle = \frac{1}{\sqrt{2}}(|f_i\rangle + |g_i\rangle), |f_i\rangle = \frac{1}{\sqrt{2}}(|f_i\rangle - |g_i\rangle)$; T represents a transformation $|g\rangle_i \to |e\rangle_i$ and S represents a transformation $|f\rangle_i \leftrightarrow |g\rangle_i$.

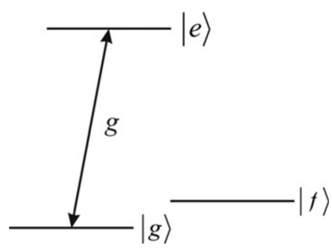

Fig. 2. The level configuration of the atoms. The transition $|g\rangle \to |e\rangle$ is resonantly coupled to the cavity mode and the additional ground state $|f\rangle$ is not coupled to the cavity mode.

The transition $|g\rangle \to |e\rangle$ is resonantly coupled to the cavity mode with the coupling constant g. The transition $|e\rangle \to |f\rangle$ is dipole forbidden. The quantum information is encoded in the ground states $|g\rangle$ and $|f\rangle$.

For clearness, we first show the experimental setup of our scheme in Fig. 3. Two distant atoms are trapped in two separate single-mode optical cavities, respectively. We assume here that atoms are simultaneously interacting with single-mode cavities and driven by strong classical fields.

Each atom is first entangled with the corresponding cavity mode via resonant interaction. After the atom–cavity interaction, photons are allowed to leak from the two cavities and will be mixed on a beam splitter destroying the initial state, and finally, photons leaking out of the cavities will be detected by the photon-detectors, which collapse the two distant atoms to an entangled state.

Assume that the atom 1 in the cavity 1 is initially in an arbitrary pure state

$$|\varphi_1\rangle = a_1|f_1\rangle + b_1|g_1\rangle, \quad (1)$$

where a_1 and b_1 are unknown coefficients. The two cavities are both initially in the vacuum state $|0\rangle$. The first step is the transfer of one photon to the cavity through a half-cycle of the vacuum Rabi oscillation of the atom-cavity system. The state $|g_1\rangle$ is excited by the vacuum Rabi half-cycle to $|e_1\rangle$, which leads to

$$|\varphi_1'\rangle = a_1|f_1\rangle + b_1|e_1\rangle. \quad (2)$$

The emission or non-emission of a photon depends on whether the initial state is $|g_1\rangle$ or $|f_1\rangle$, providing the essential tool for generating entanglement between the atom and cavity field. Experimental demonstration of atom–atom entanglement has been reported [29]. We divide the two atoms into separated cavities, which can be connected through the detection of leaking photons [18,30–33]. The experiment is based on only cavity QED system. To be specific, atoms are controlled in a single-mode cavity to achieve entanglement state. We consider that the atom

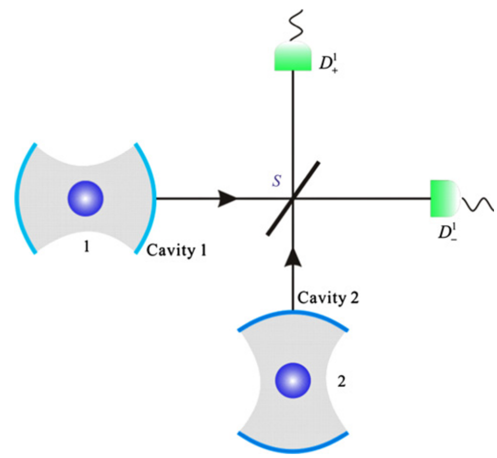

Fig. 3. The experimental setup for two-atom maximally entangled states. Atoms are trapped in separate cavities. Photons leak through the sides of the cavity facing the beam-splitter S and then are detected by the photo-detectors. D_+^1 and D_-^1.

2 is in the arbitrary state

$$|\varphi_2\rangle = a_2|f_2\rangle + b_2|g_2\rangle, \quad (3)$$

where a_2 and b_2 are the coefficients. Because the state $|g_2\rangle$ is excited by the vacuum Rabi half-cycle to $|e_2\rangle$, which can lead to

$$|\varphi_2'\rangle = a_2|f_2\rangle + b_2|e_2\rangle. \quad (4)$$

In the interaction picture, the conditional Hamiltonian for the ith ($i=1,2,3$) cavity mode can be described as

$$\mathbf{H} = \mathbf{H}_i - i(\kappa/2)a_i^+ a_i - i(\Gamma/2)|e_i\rangle\langle e_i|. \quad (5)$$

where $\mathbf{H}_i = g(a_i s_i^+ + a_i^+ s_i^-)$, g is the coupling constant between atoms and cavity, a_i^+ and a_i are creation and annihilation operators for the ith cavity mode, s_i^+, s_i^- are the atomic operators. In addition, the cavity decay rate is κ and the atomic spontaneous emission rate is Γ. Then we obtain the evolution

$$|e_i\rangle|0_i\rangle \to e^{-(\kappa+\Gamma)t/4}\left[\left(\cos(\alpha t) + \frac{\kappa-\Gamma}{4\alpha}\sin(\alpha t)\right)|e_i\rangle|0_i\rangle - i\frac{g}{\alpha}\sin(\alpha t)|g_i\rangle|1_i\rangle\right], \quad (6)$$

where

$$\alpha = \sqrt{g^2 - (\kappa-\Gamma)^2/16}. \quad (7)$$

When the interaction time t meets the condition that $\tan(\alpha t) = 4\alpha/(\Gamma-\kappa)$, the whole system evolves to

$$|\Psi_1\rangle = \left(a_1|f_1\rangle|0_1\rangle - i\frac{g}{\alpha}\sin(\alpha t_1)e^{-(\kappa+\Gamma)t_1/4}b_1|g_1\rangle|1_1\rangle\right) \otimes \left(a_2|f_2\rangle|0_2\rangle - i\frac{g}{\alpha}\sin(\alpha t_1)e^{-(\kappa+\Gamma)t_1/4}b_2|g_2\rangle|1_2\rangle\right). \quad (8)$$

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